

# **DIAGNOSTICS AND CONTROL OF NATURAL GAS FIRED FURNACES VIA FLAME IMAGE ANALYSIS**



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**PI: Shahla Keyvan  
University of Missouri-Rolla**

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# PROJECT PARTNERS

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University of Missouri

&

Lehigh University



# **PROJECT SUPPORT**

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**(Excluding in-kind cost share by manufacturing companies)**

- **U.S. DOE  
OIT Sensors and Controls Program**
- **Missouri Department of Economic Development  
Manufacturing Research and Training Center (MRTC)**
- **University of Missouri-Rolla (UMR)  
Intelligent Systems Center**

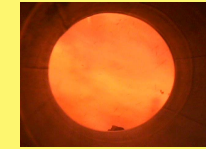


# PROJECT SCOPE

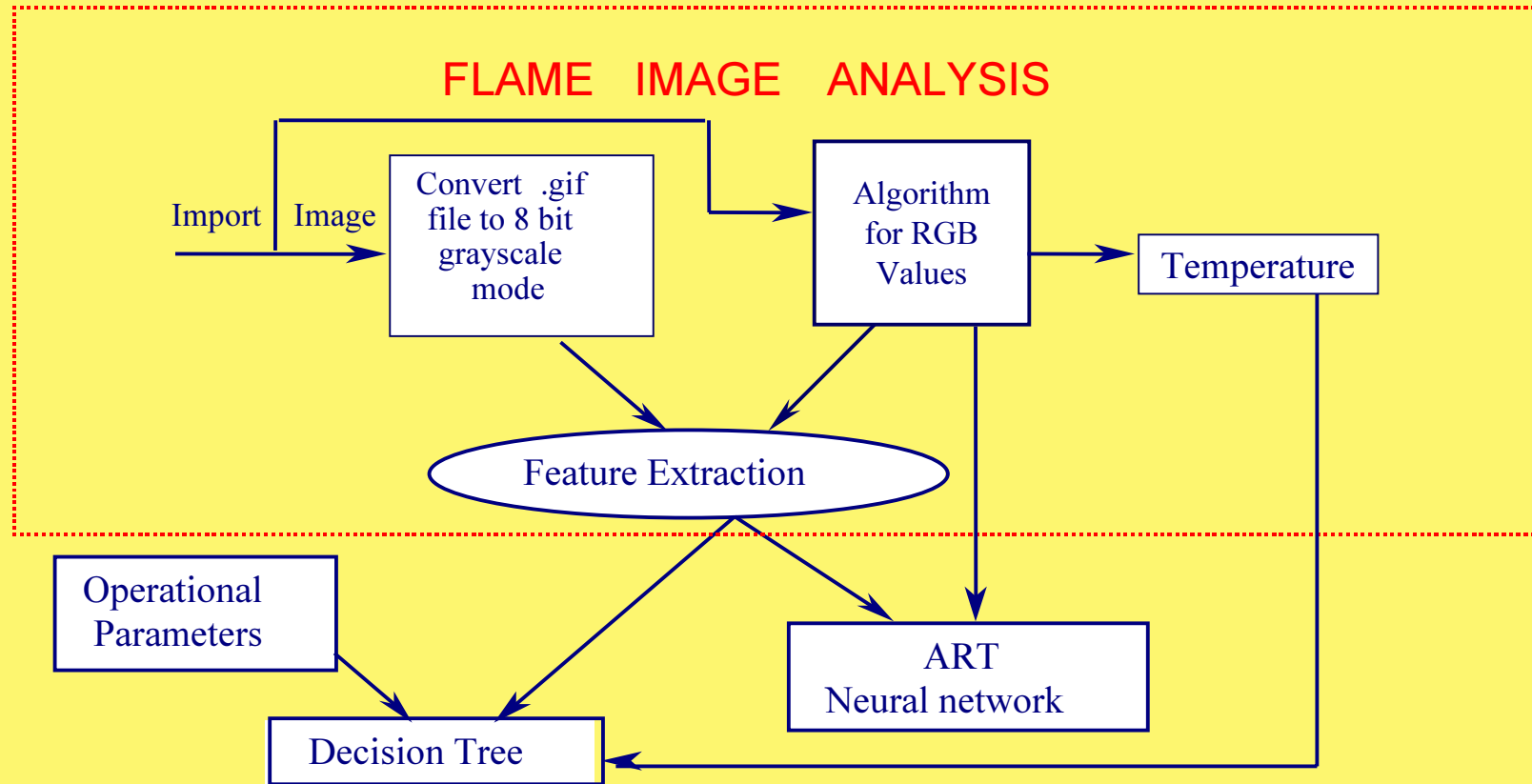
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Flame video images and fiber optics spectrometry data together with advanced image analysis and artificial intelligence techniques are used to obtain information for optimal internal control of gas fired furnaces. This includes guidance for balancing air/fuel ratios between individual burners on multi-burner furnaces.

This on-line diagnostic and control system offers great potential for improving furnace thermal efficiency, lowering NO<sub>x</sub> and carbon monoxide emissions, and improving product quality.



Sample Flame Image



**Flame Image Analysis Components and a Sample Flame Image**



# APPLICATIONS & POTENTIAL BENEFITS

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- Flame Image Analyzer adaptable to various types of furnaces.
- Low-cost retrofit for implementing advanced process control for natural gas-fired furnaces used in the glass industry.
- Real-time process control of multi-burner, natural gas fired furnaces for melting scrap and recycled materials in the aluminum industry.



# APPLICATIONS & POTENTIAL BENEFITS

## (Cont.)

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- Improved diagnostic capabilities (detect burner malfunction).
- Improved individual burner performance (burner balancing allows operation at reduced excess air levels resulting in improved thermal efficiencies and reduced emissions).
- For a large gas fired boiler ( $5.4 \times 10^9$  BTU/hour), a ten percent reduction in nitrogen oxide emissions would result in savings of about \$1,000,000 per year from NO<sub>x</sub> credits.
- For the same gas fired boiler, a small reduction in fuel consumption of 0.5% would result in fuel savings of over \$250,000 per year.
- Improved product quality due to greater temperature uniformity and less burner maintenance problems.



## EQUIPMENT

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Water cooled periscope by Lenox Instrument Company

- High temperature lens and water cooling system  
(withstands temperatures up to 3500 °F)
- Color CCTV camera
- Light volume control
- Direct viewing and 90° field of view



## EQUIPMENT (Cont.)

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### Spectrometer

- S-2000 Ocean Optics spectrometer  
(spectral window  $\sim$  200-1100 nm)
- Halogen lamp (color temperature 3100 K)
- Fiber optic cable (2 m range)
- SAD 500 computer interface
- Integration time (5 ms to 60 s)



# **PROJECT TECHNICAL MILESTONES**

## **PHASE I**

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### **Phase I: Feasibility Study, February 2000-2001**

Three major tasks were carried out:

- Data/image acquisition
  - Natural gas-fired boiler at Penn State University
  - Natural gas and oxy-fuel-fired glass furnace at the University of Missouri-Rolla
- Flame image analysis
- Pattern recognition



## FACILITIES

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1. Single-burner, multi-fuel research boiler with the following characteristics:
  - A 2 MBtu/hr firing rate equipped with a CEM system for emissions monitoring.
  - Water-cooled combustion chamber with 288 ft<sup>2</sup> of heating surface.
  - Capabilities to vary air/fuel ratio, burner swirl number and combustion air preheat.
  - Eighteen view ports along the side walls plus additional view ports at the front and rear-end of the boiler.



## FACILITIES (Cont.)

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2. Thermal flame glass furnace designed to carry out simulation and parametric studies of industrial glass tanks with the following characteristics:
  - A 0.1-0.5 MBtu/hr pilot-scale furnace that can melt from about 100 lbs of glass/day to 2,000 lbs of glass/day.
  - Air-gas and oxy-fuel combustion. Can accommodate various types of instruments through existing ports. New ports can be added as needed.
  - Furnace design allows different burner types (including commercial oxy-fuel burners) and burner arrangements, and positioning.



## PHASE I ACCOMPLISHMENTS

- Equipment Acquisition
- Data Acquisition
  - Research Boiler
  - Pilot Scale Glass Furnace
- Spectrometer Results

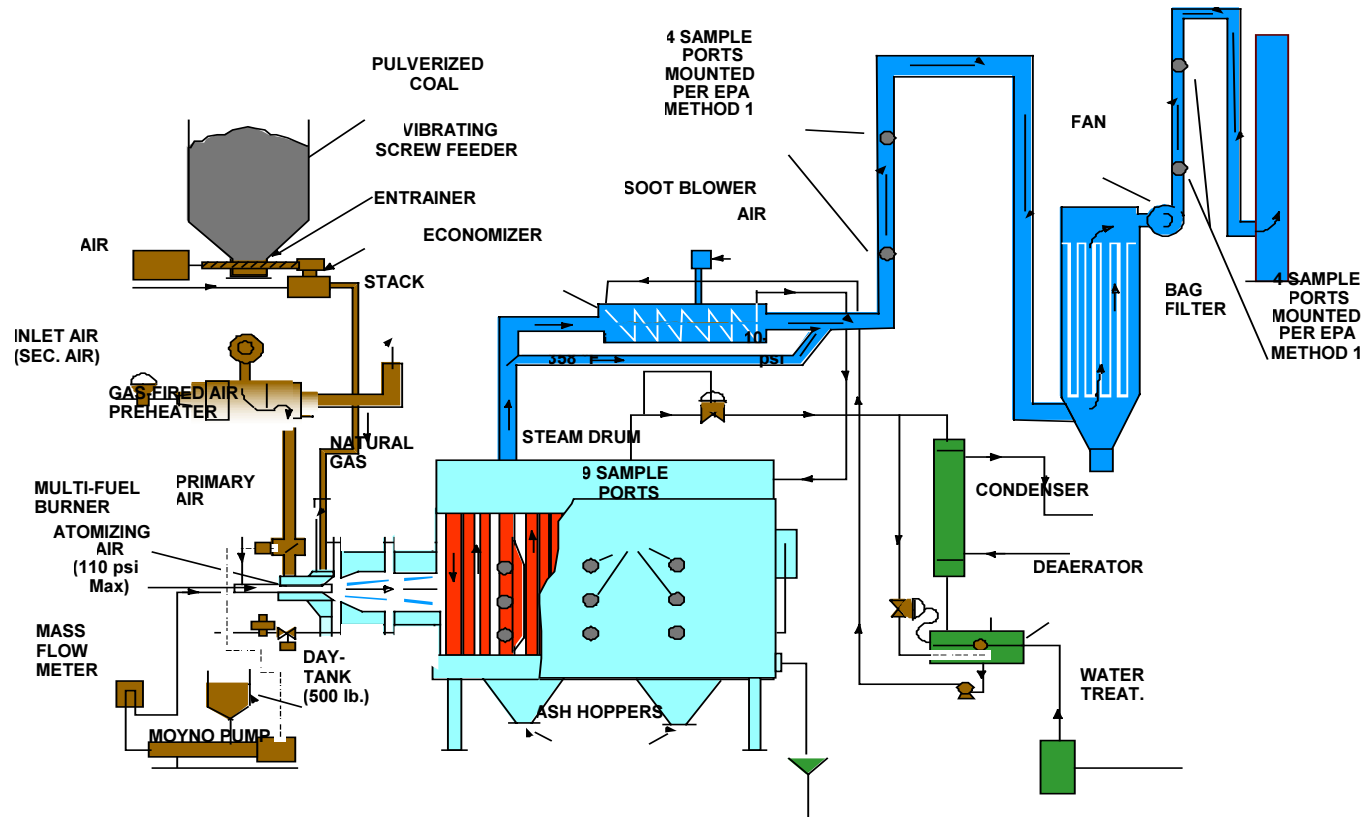


## PHASE I ACCOMPLISHMENTS (Cont.)

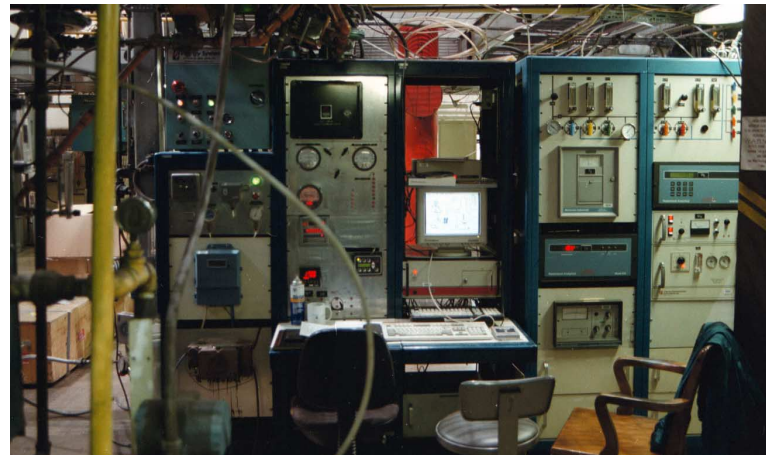
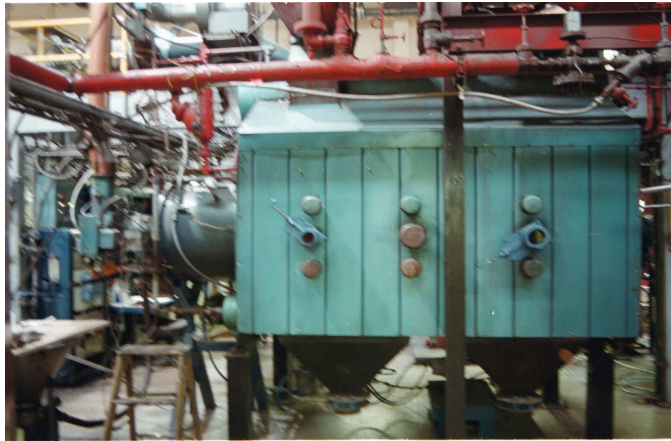
- Flame Image Analysis
  - Image Processing
  - Feature Extraction
- Image Classification
  - Neural Networks
    - Fuzzy ARTMAP (Supervised Network)
    - ART2-A (Unsupervised Network)

# Data Acquisition-Research Boiler

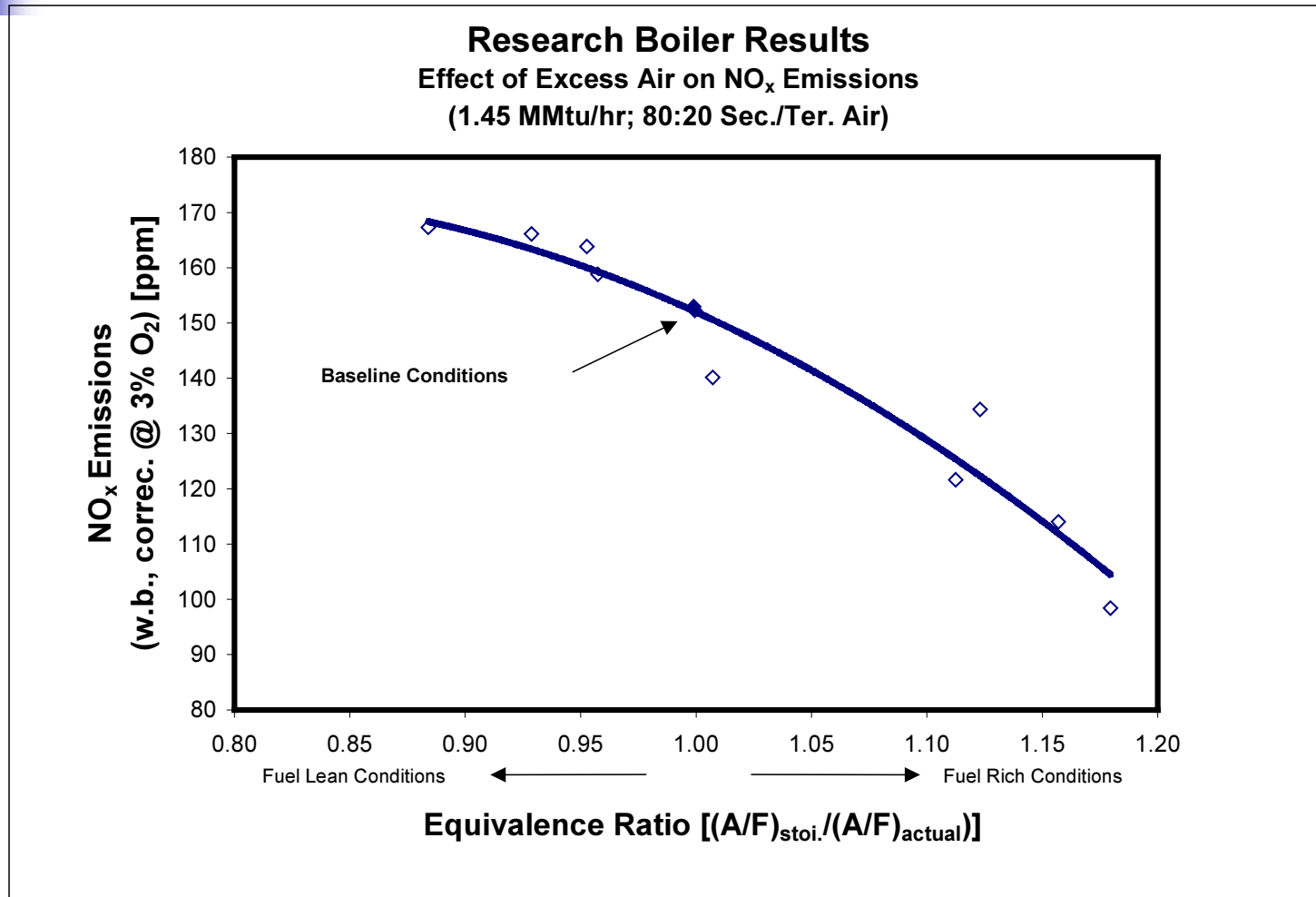
## Schematic Diagram of Research Boiler



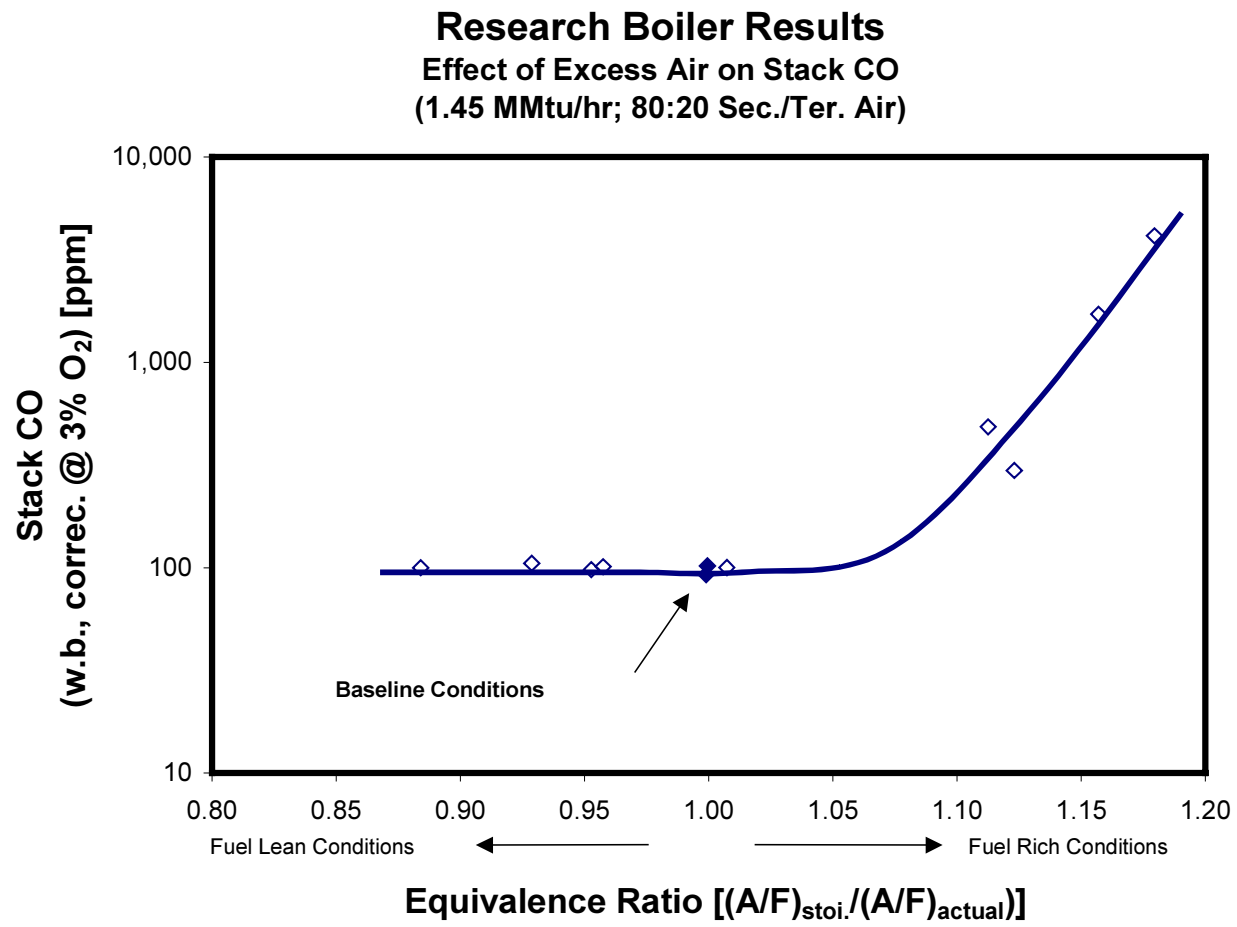
# RESEARCH BOILER FACILITY



# RESEARCH BOILER RESULTS

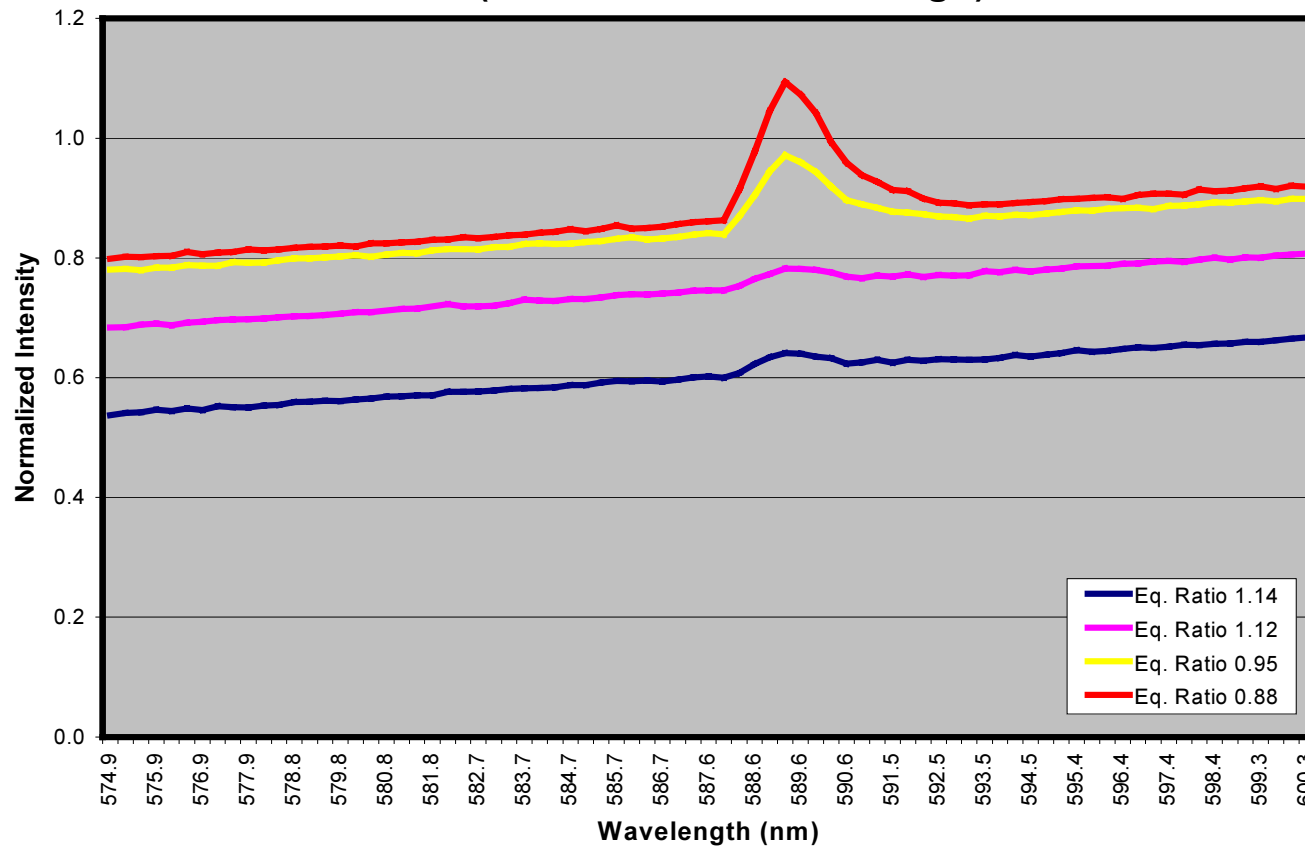


# RESEARCH BOILER RESULTS



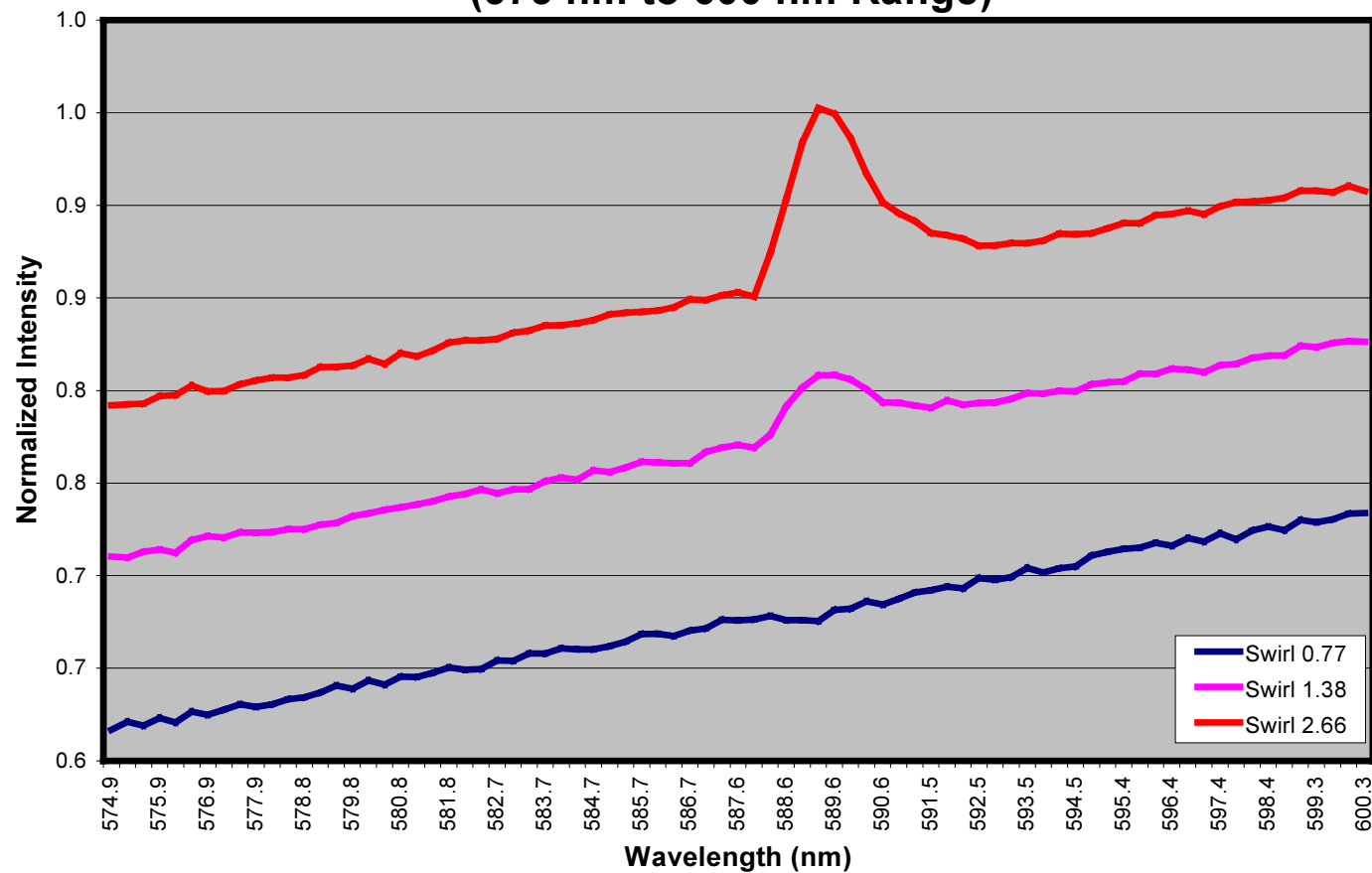
# EMISSION LINES COMPARISON

**Spectral Comparison at Different Air Fuel Ratios  
(575 nm to 600 nm Range)**



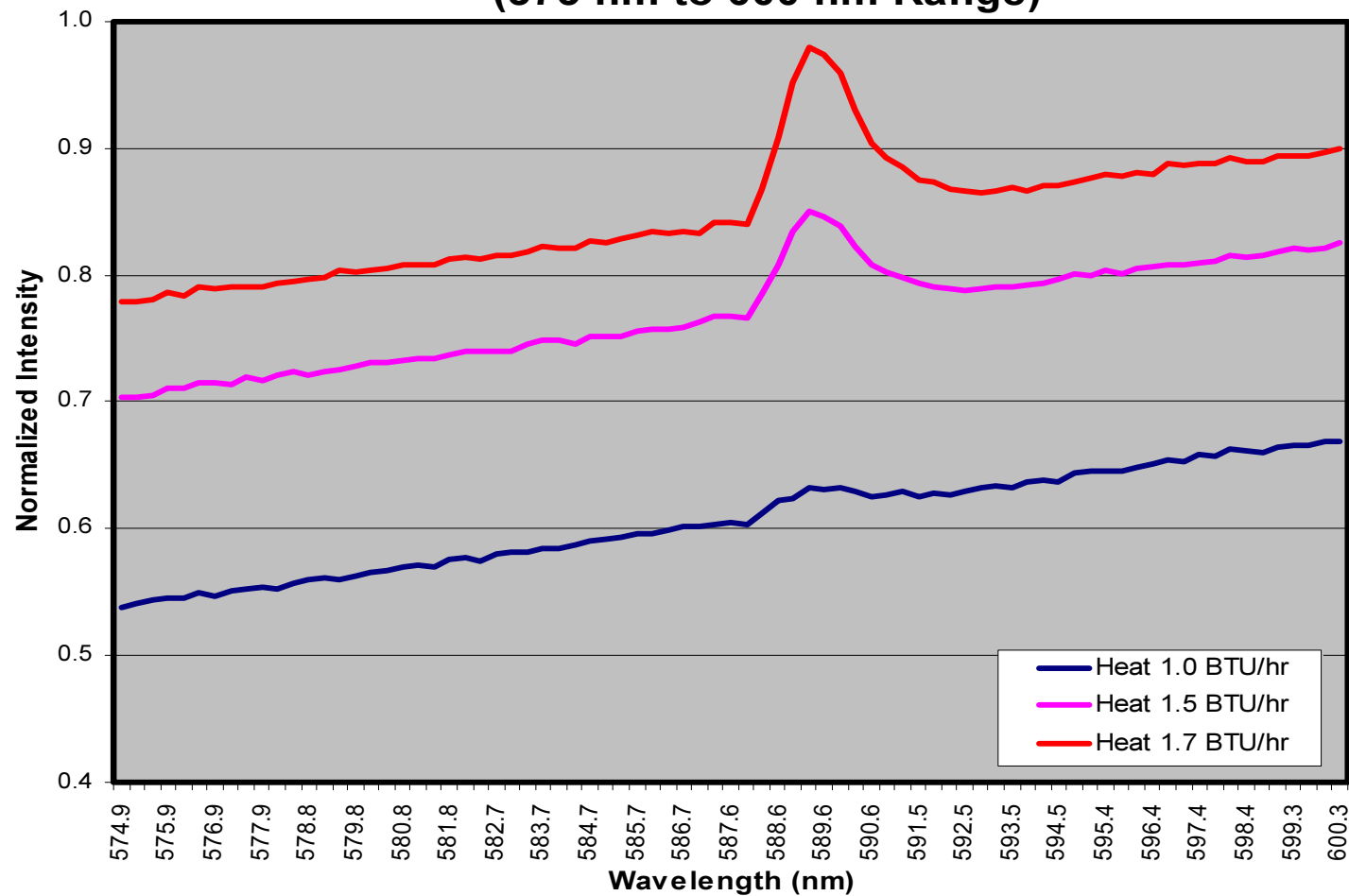
# EMISSION LINES COMPARISON

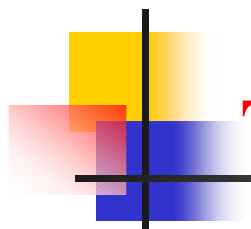
**Spectral Comparison at Different Burner Swirl Numbers  
(575 nm to 600 nm Range)**



# EMISSION LINES COMPARISON

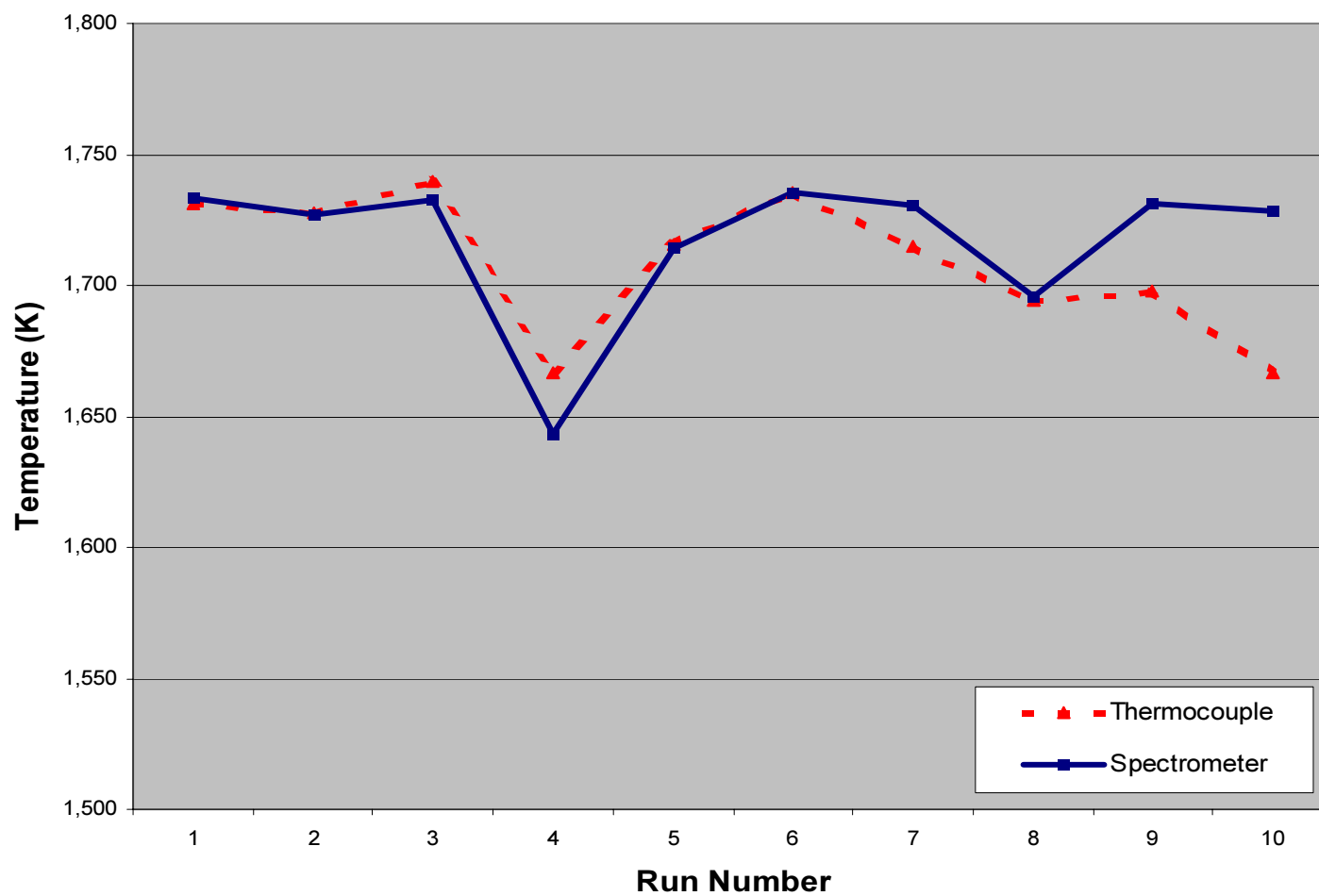
Spectral Comparison at Different Firing Rates  
(575 nm to 600 nm Range)





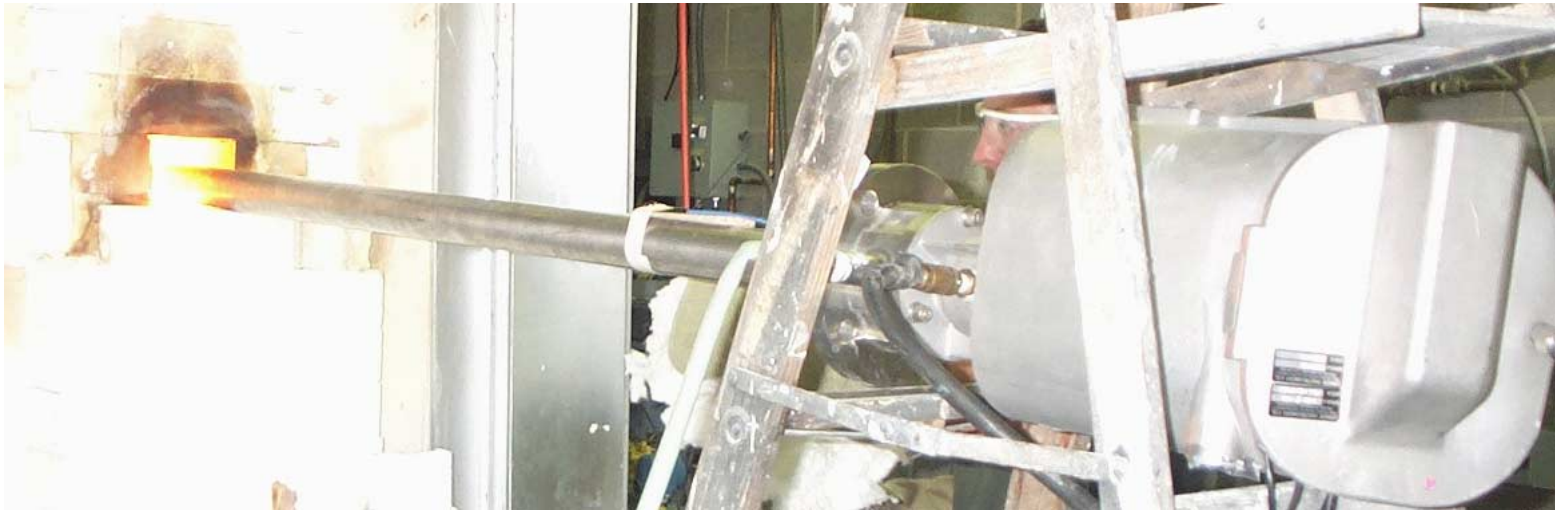
# TEMPERATURE COMPARISON

## Temperature Comparison



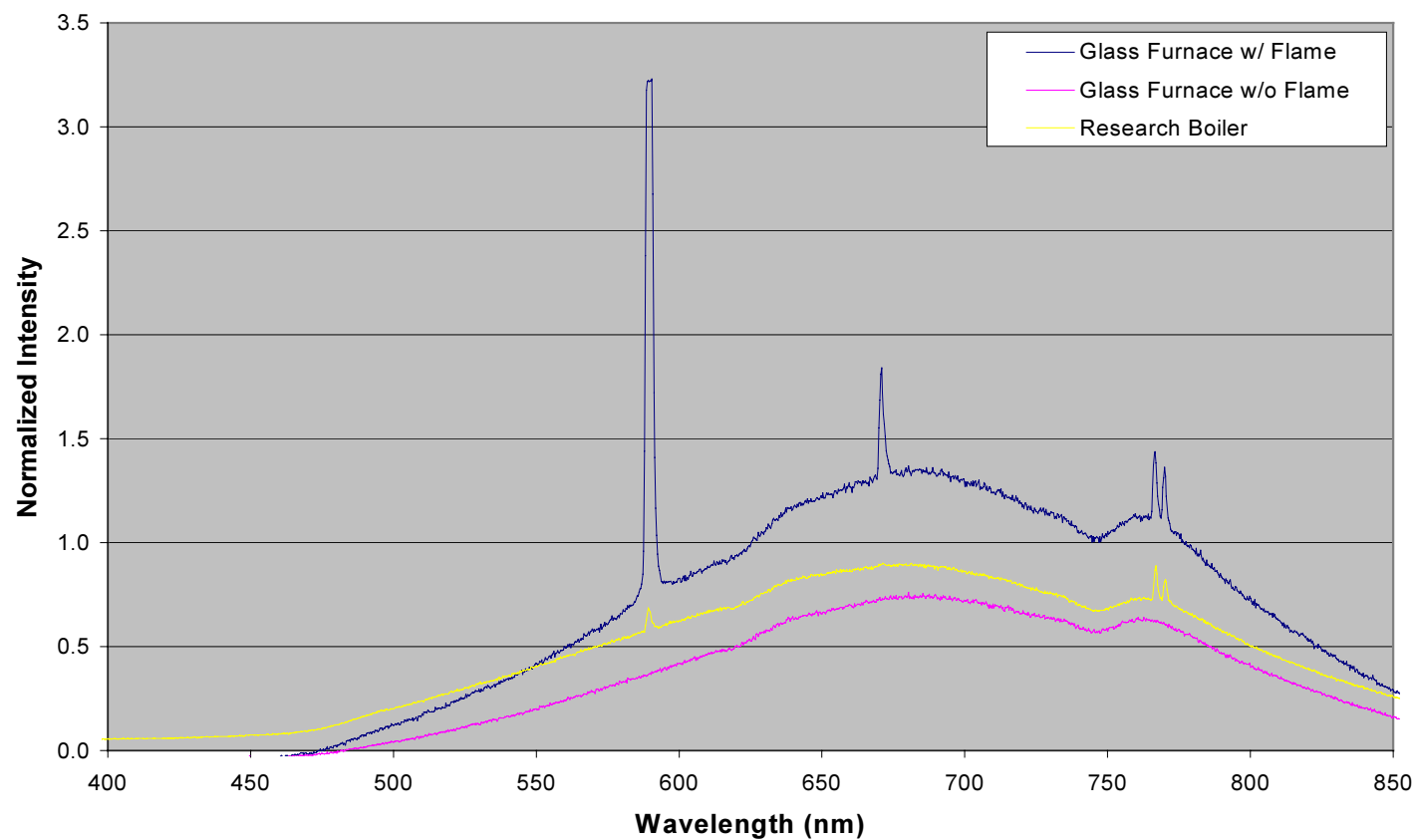
# Data Acquisition-Glass Furnace

Pilot Scale Glass Furnace with CCD Camera in Operation



# EMISSION LINES COMPARISON

## Spectral Comparison

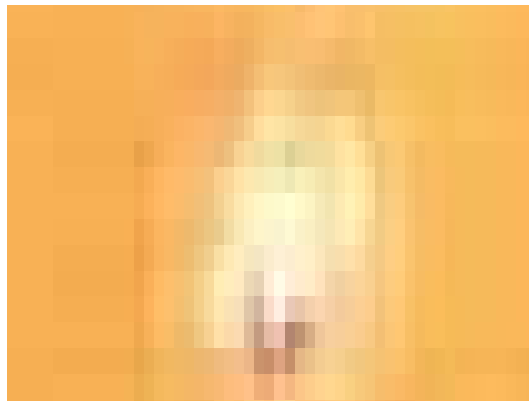




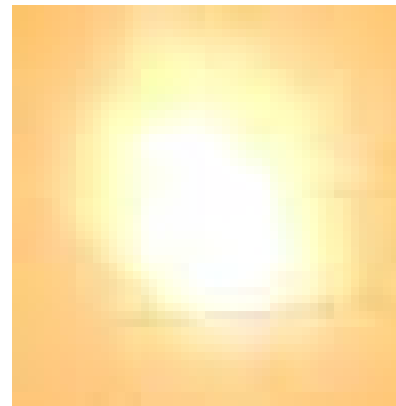
## Sample Flame Images

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### Pilot Scale Glass Furnace



(a)



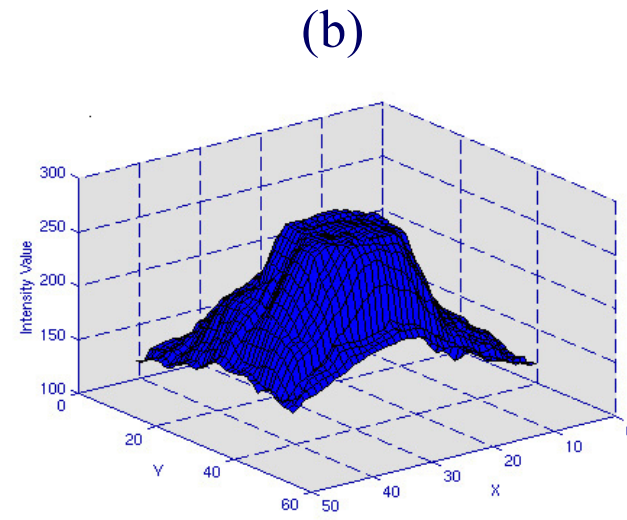
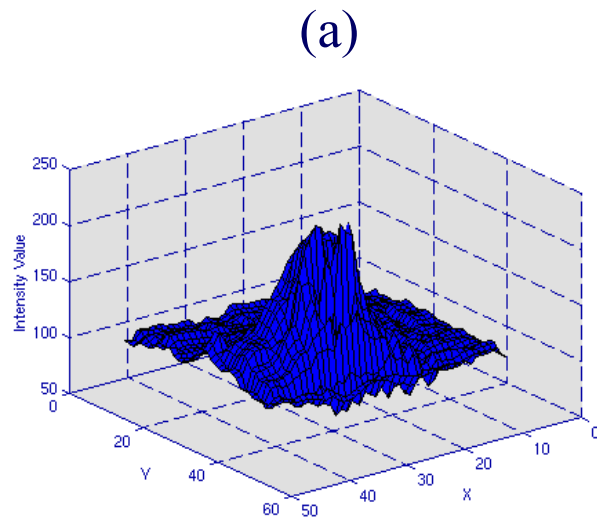
(b)



# Flame intensities

## Pilot Scale Glass Furnace

Histogram of the Intensities of the flame images





# Sample Flame Images

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## Research Boiler

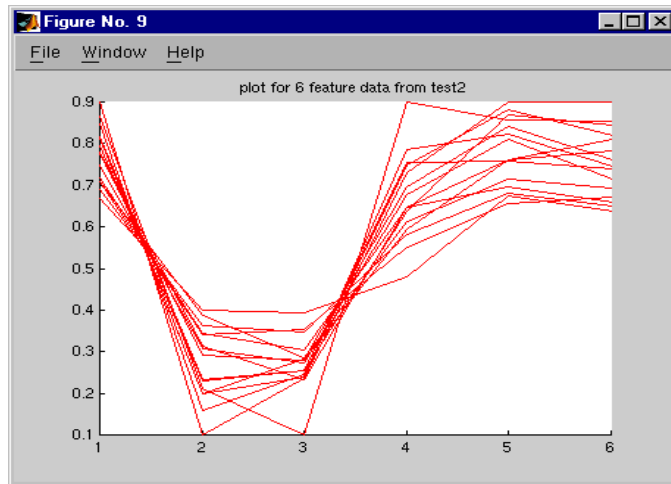


(a)

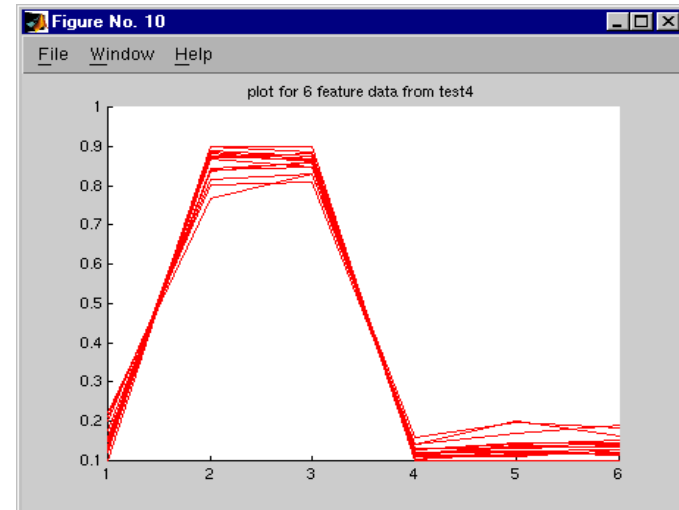


(b)

# Feature Extraction Results



**$\Phi = 1.16$ , CO = 1,701 ppm,  
NO<sub>x</sub> = 114 ppm**



**$\Phi = 0.88$ , CO = 100 ppm,  
NO<sub>x</sub> = 167 ppm**



# **SIMULATION**

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## **Flame Image Classification** **(Proof of Concept)**

**To play this simulation game click on Game**

**[Game](#)**



# PROJECT TECHNICAL MILESTONES

## PHASE II

### Phase II: Full Scale Furnace Integration February 2001-2003

PHASE II	Year 1				Year 2			
	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
<b>Comprehensive data acquisition and analysis</b>								
Single and multi-burner glass furnace								
Single and multi-burner aluminum furnace								
<b>Virtual temperature sensing</b>								
<b>Flame image analysis by Decision Tree</b>								
<b>Prototype system development</b>								
<b>Verification using full-scale furnaces</b>								



## **DATA ACQUISITION-PHASE II**

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**Phase II (in progress)**

**Commercial Furnace/Multi-Burner**

**Sample Flame Images:**

Commercial Glass Furnace (Two-Burners)

